Evidence for a Phase Transition Near Optimum Doping in the Cuprates (1995 to present)

G.S. Boebinger, Yoichi Ando, A. Passner, T. Kimura, M. Okuya, J. Shimoyama, K. Kishio, K. Tamasaku, N. Ichikawa, and S. Uchida,


“Insulator-to-metal crossover in the normal state of La$_{2-x}$Sr$_x$CuO$_4$ near optimum doping.”
Overview of the MagLab User Program
National High Magnetic Field Laboratory

Florida State University

Los Alamos National Laboratory

University of Florida

Advanced Magnetic Resonance Imaging and Spectroscopy Facility

1.4 GW Generator

45T Hybrid DC Magnet

101T Pulse Magnet
10mm bore

11.4T MRI Magnet
400mm warm bore

High B/T Facility
17T, 6 weeks at 1mK

900MHz, 105mm bore
21T NMR/MRI Magnet
The MagLab is its User Program

In 2012, the MagLab hosted experiments by more than 1350 users from 159 institutions across the United States...

...and a total of 277 institutions throughout the world.
The MagLab is its User Program

MagLab users publish about 440 refereed publications annually:

2009-2013 Publications

- 2200 Total Publications
- 28 PNAS
- 63 Nature Journals
- 147 Physical Review Letters
- 318 Physical Review B
- 47 PRB (Rapid Comm)
- 59 JACS
Hosting ~ 1350 Users annually: 55% senior investigators, 15% postdocs, 30% students
Hosting ~ 425 Principal Investigators annually, approximately 20% are new every year
MagLab Technology  Leads the World

- **PULSED MAGNETS**
  - Orange: Short Pulse (1-10 msec)
  - Blue: Long Pulse (100-5000 msec)

- **CONTINUOUS (DC) MAGNETS**
  - Green: Hybrid (Resistive + Superconducting)
  - Purple: All Resistive

- **SUPERCONDUCTING MAGNETS**
  - Red: Demonstration Test Coils
  - Orange: Commercial Magnet Systems

Records when MagLab was created (1990):
- 17.5T IGC, Inc.
- 23.4T Bruker, Inc.*
- 35T MagLab
- 36T MagLab
- 40T MagLab
- 60T MagLab
- 45T MagLab
- 31T Grenoble
- 24T Grenoble
- 40T Amsterdam
- 68T MIT
MagLab Technology Leads the World

PULSED MAGNETS
- Short Pulse (1-10 msec)
- Long Pulse (100-5000 msec)

CONTINUOUS (DC) MAGNETS
- Hybrid (Resistive + Superconducting)
- All Resistive

SUPERCONDUCTING MAGNETS
- Demonstration Test Coils
- Commercial Magnet Systems

Current Records
- 101T MagLab
- 60T MagLab
- 45T MagLab
- 37.5T Nijmegen
- 36T MagLab
- 35T MagLab
- HTS Test Coil
- 23.4T Bruker, Inc.*

Records when MagLab was created (1990)
- 68T MIT
- 40T Amsterdam
- 31T Grenoble
- 24T Grenoble
- 17.5T IGC, Inc.

22 years later…

Click on “Search Pubs” for all refereed publications from the user program.

Click on “Publications & Reports” for:

- MagLab Reports, our scientific outreach magazine
- Flux, our outreach magazine for the general public
To request magnet time, apply online:  www.magnet.fsu.edu

We host ~ 1400 magnet users annually
...20% of our Principal Investigators are first-timers.

...we look forward to hosting you at the MagLab
The Cuprates: The Early Years
Key Ingredients for Cuprate Superconductivity

$T_c = 94 \text{ K}$  $T_c = 94 \text{ K}$  $T_c = 39 \text{ K}$  $T_c = 90 \text{ K}$

Barisić, N et al., PNAS (2013)
First Key Ingredient for (‘Cuprate’) High-Temperature Superconductors: the Copper – Oxygen Plane

The 2D Copper-Oxygen Plane... the playground of high-temperature superconductivity

With one electron on each Copper atom, the electrons cannot move... and you have an insulator
Second Key Ingredient for (‘Cuprate’) High-Temperature Superconductors:

Removing electrons from the Copper – Oxygen Plane

With one electron on each Copper atom, the electrons cannot move... and you have an insulator

However, remove ~5% to ~27% of the electrons...
...and you have a High-Tc Superconductor

For more than a dozen different materials, the same 16% doping... optimizes superconductivity (highest transition temperature)
Second Key Ingredient for (‘Cuprate’) High-Temperature Superconductors:

Removing electrons from the Copper – Oxygen Plane

For more than a dozen different materials, the same 16% doping...
...optimizes superconductivity (highest transition temperature)
...optimizes linear-T resistivity
Phase Diagram of the High-\(T_c\) Superconductors

**Generalized Phase Diagram**

- 2D strange metal
- 3D metal
- 0 < \(T_c\) < \(-160\) K
- Superconductor

\[ \delta = \% \text{ of } \text{Cu}^{3+} \text{ in planes} \]

Figure 3.26. “Generalized Phase Diagram” as seen (roughly) in \((La - Sr)CuO_4\).
Suppressing Superconductivity with Magnetic Fields

to Probe the Abnormal Normal State in the Zero-Temperature Limit
The Abnormal Normal State of the High-$T_c$ Superconductors


Using 60 teslas...to suppress the superconducting state and reveal the normal-state phase diagram
Pulsed Magnet Facility, Bell Laboratories (1990-1998)

- Maximum field: 72 T (60 T routine)
- Pulse repetition rate: Three 60T-pulses/hr
- Energy in magnetic field: 1 stick of dynamite

Energy = 1 stick of dynamite
Energy = 1 jelly doughnut
Challenges in Producing High Magnetic Fields

**Pressure Under Water**
- 12 feet Ears: 6 pounds per square inch
- 2000 feet Submarine: 1000 psi
- 12,000 feet Ocean Floor: 6000 psi

**Pressure inside NHMFL Pulsed Magnets**
- 800,000 gauss Pulsed Magnet: 200,000 psi
  (which equals 1.4GPa or 130 kg per square millimeter)
  (which is more pressure than most materials can handle)

Strong Electromagnets Generate BIG Forces

The Niobium ribbons work (sort of) like steel bars in cement…

…except the nano-composite is five times stronger than either constituent
FIG. 1. In-plane resistivity $\rho_{ab}$ versus magnetic field for the $x = 0.08 \text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ single crystal at various temperatures.

FIG. 2. Temperature dependence of $\rho_{ab}$ in 0, 10, 20, and 60 T, obtained from the pulsed magnetic field data. The solid line shows the zero-field resistive transition. The inset contains the low-temperature data.
Logarithmic Divergence of both In-Plane and Out-of-Plane Normal-State Resistivities of Superconducting La$_{2-x}$Sr$_x$CuO$_4$ in the Zero-Temperature Limit

Yoichi Ando,* G. S. Boebinger, and A. Passner
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Tsuyoshi Kimura and Kohji Kishio
Department of Applied Chemistry, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan
(Received 18 August 1995)

The low-temperature normal-state resistivities of underdoped La$_{2-x}$Sr$_x$CuO$_4$ crystals with $T_c$ of 20 and 35 K were studied by suppressing the superconductivity with pulsed magnetic fields of 61 T. Both in-plane resistivity $\rho_{ab}$ and out-of-plane resistivity $\rho_c$ are found to diverge logarithmically as $T/T_c \to 0$. Logarithmic divergence is accompanied by a nearly constant anisotropy ratio, $\rho_c/\rho_{ab}$, suggesting an unusual three-dimensional insulator.
Logarithmic Divergence of the In-Plane Resistivity of Underdoped $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$

$\rho_{ab}^\text{BSLCO} = \frac{\text{m}^2\text{cm}}{\Omega}$

$k_F = 1 \ @ 3.1 \text{ m}\Omega\text{cm}$
**LOGARITHMIC DIVERGENCES….WHAT THIS IS NOT**

### Weak Anderson Localization

*Time-reversed scattering sequences give rise to coherent backscattering*

Small logarithmic decrease in conductivity in two dimensional systems.

*NOT LIKELY, because...*

Large effect seen in resistivity. Persists even in 60T magnetic field.

### Kondo Scattering

*Spin-flip scattering of conduction electrons from local magnetic moments*

Logarithmic increase in resistivity in three dimensions

*NOT LIKELY, because...*

Persists in 60T magnetic field even for temperatures $k_B T < g\mu_B H$

### Enhanced Localization due to Electron Interactions

*Logarithmic decrease in the density of states near the Fermi energy*

Logarithmically suppressed conductivity in two-dimensional systems and carrier concentration due to reduced density of states

*NOT LIKELY, because...*

Large effect seen in resistivity. No divergence seen in Hall effect.
“Insulator-to-metal crossover in the normal state of La$_{2-x}$Sr$_x$CuO$_4$ near optimum doping.”

$\rho_{ab}$ (m$\Omega$-cm) vs. $T$ (K) for LSCO single crystals.

$\rho_{ab}$ (m$\Omega$-cm) vs. $T$ (K) for BSLCO single crystals.

Underdoped Optimum Overdoped

Logarithmically Divergent Resistivity in Underdoped Cuprates

**Similarities** between the Insulator-to-Metal crossover in BSLCO and LSCO:

--- occurs under the superconducting ‘dome’

--- occurs at the same normalized resistivity, at $k_F l \sim 15$.

![Graph showing resistivity vs. temperature for BSLCO and LSCO](image)
Questions: Metal-Insulator Crossover in the Low-Temperature Normal State

\[ \text{La}_{2-x} \text{Sr}_x \text{CuO}_4 \]

Sharp Insulator-to-Metal Crossover
---at optimum doping

Evidence of a Quantum Critical Point?
---near optimum doping
---where linear-T resistivity has been attributed to critical behavior

\[ \text{Bi}_{2} \text{Sr}_{2-x} \text{La}_x \text{CuO}_{6+\delta} \]

No evidence of weird resistivity behavior at optimum doping in BSLCO...
other than the usual linear-T resistivity.

If there were a Quantum Critical Point at optimum doping in BSLCO...
---between two metallic states.
---underdoped metal exhibits unusual scattering or localization.
---would like to find experimental evidence in transport.
Logarithmic upturn in resistivity in underdoped, non-superconducting YBCO

Nicolas Doiron-Leyraud,1 Mike Sutherland,2 S. Y. Li,1 Louis Taillefer,1,3,* Ruixing Liang,4,3 D. A. Bonn,4,3 and W. N. Hardy4,3

PRL 97, 207001 (2006)
Linear-T to zero temperature as evidence of a quantum critical point

La_{2-x}Sr_xCuO_4

K.H. Kim, N. Harrison, G.S. Boebinger (Los Alamos);
Switching from Resistivity to Hall Measurements
Hall Effect in Bi\textsubscript{2}Sr\textsubscript{2-x}La\textsubscript{x}CuO\textsubscript{6+d}

- Unusual Temperature-dependence of Hall coefficient not understood

- What happens below $T_c$?
Low Temperature Normal State Hall Effect

Hall Resistivity

\( \rho_{xy} (\mu \Omega \text{cm}) \)

\( H(T) \)

\( \rho_{xy}(H) \) for Bi\(_{2}\)Sr\(_{2-x}\)La\(_{x}\)CuO\(_{6+d}\) with La \( x = 0.49 \)

\( T_c = 33K \)

In-plane Resistivity

\( \rho_{ab}(\mu \Omega \text{cm}) \)

\( B(T) \)

\( \rho_{ab}(B) \) for Bi\(_{2}\)Sr\(_{2-x}\)La\(_{x}\)CuO\(_{6+d}\) with La \( x = 0.49 \)

\( T_c = 33K \)

High-field Hall voltage is linear in field

\( p = 0.18 \leq p \leq 0.16 \leq 0.15 \leq 0.14 \leq 0.12 \leq 0.10 \)

Bi\(_{2}\)Sr\(_{2-x}\)La\(_{x}\)CuO\(_{6+d}\) with La \( x = 0.49 \)

\( T_c = 33K \)
Low Temperature Hall Effect

$R_{H}[10^{-3} \text{cm}^3\text{C}^{-1}]$

$R_{H}(e/N_{\text{cell}}$

$T(K)$

$0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100$

$0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8$

La=.84
La=.73
La=.51
La=.49
La=.39
La=.23
Low Temperature Hall Effect

\( R_H (e/NV_{cell}) \) vs. \( T(K) \)

- \( La = 0.84 \)
- \( La = 0.73 \)
- \( La = 0.51 \)
- \( La = 0.49 \)
- \( La = 0.39 \)
- \( La = 0.23 \)
Insulator-to-Superconductor boundary
(the Underdoped Side of the Superconducting Dome)

\[ \text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+d} \]

For nearly non-superconducting sample...depletion of carriers as \( T \rightarrow 0 \) K

\[ p=0.10, \ T_c = 1.5 \text{K} \]

Resistivity diverges much faster than logarithmically...consistent with strong localization

\[ p=0.10 \]

\[ T_c = 1.5 \text{K} \]
“Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor”


Change in T-dependence
...no feature at zero-field Tc
...lose temperature dependence as \( T \to 0 \)

...gives an anomaly at doping corresponding to the at highest Tc
We may understand the high-temperature behavior of the Hall number... 

...but not the peak at low temperatures 

...at temperatures below $T_c$ 

...and centered on the sample with the highest $T_c$

Low-Temperature Hall Number in Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+d}$

Onset of carriers yields onset of superconducting phase

Jump at doping with Highest Tc
Hall Number is correlated with $T_c$

In the underdoped regime…
$n_{Hall}$ shows remarkably linear correlation with $T_c$.

…but not in the overdoped regime…
Hall coefficient becomes $T$-independent at low-$T$ near optimum doping in BSLCO ---suggesting a measurement of the Hall number.

Linear relation between $T_c$ and the low-$T$ Hall number ---suggests phase stiffness governs superconducting transition in underdoped samples

Sharp anomaly in doping dependence of the Hall number at optimum doping ---suggesting change in the Fermi Surface

...suggests a Quantum Critical Point governs High-$T_c$ Superconductivity

Quantum Phase Transition at Optimum-Doping: Peak in Hall number also seen in LSCO

LSCO  F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando & GSB

with a linear-T resistivity
Quantum Phase Transition at Optimum-Doping: Peak in Hall number also seen in LSCO

LSCO  
F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando & GSB  

with a linear-T resistivity

Optimum Doping
Quantum Phase Transition at Optimum-Doping: Peaks in Hall number seen in two systems

First observed in Bi-2201 in 2003

“Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor”

Now confirmed in another high-$T_c$ (LSCO)

“Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping.”

Evidence of phase transition (but no peak) also reported in electron doped PrCeCuO$_4$

Evidence of phase transition at optimum doping also reported in electron doped PrCeCuO$_4$ \((M-I \text{ transition and Hall changes sign})\)

![Graph](image)

FIG. 2. (Color online) (a) The resistivity of \(x=0.12, 0.13, 0.14, 0.15, \text{ and } 0.16\) films at zero field and at \(\mu_0H=14T\|c\) axis. (b) The Hall coefficient of \(0.12 \leq x \leq 0.18\) films \((T=2 \text{ K})\).

Transport evidence of a magnetic quantum phase transition in electron-doped high-temperature superconductors

\(W. \text{ Yu, J.S. Higgins, P. Vach & R.L. Greene, PRB 76, 020503(R) (2007)}.\)
Evidence of phase transition at optimum doping also reported in electron doped \( \text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4 \) (\textit{M-I transition and Hall changes sign})

Correlation between Fermi surface transformations and superconductivity in the electron-doped high-Tc superconductor \( \text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4 \)


arXiv:1403.7398v1
Back to Zero Magnetic Fields...
(or at least <30T)
The Signatures of the Onset of the Pseudogap
The doping dependence of $T^*$ - what is the real high-Tc phase diagram?

Fig. 3. The $^{89}$Y Knight shift for $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{7-\delta}$ with different $\delta$ values scaled as a function of $T/E_g$ (♦) $T_c = 47.5$, $p = 0.086$; (▼) $T_c = 65.8$, $p = 0.107$; (▲) $T_c = 83.2$ K, $p = 0.140$; (■) $T_c = 86$ K, $p = 0.160$; (△) $T_c = 72.1$ K, $p = 0.204$; (□) $T_c = 60$ K, $p = 0.221$; (○) $T_c = 47.5$ K, $p = 0.234$. Inset: $E_g$ values obtained from the scaling, 0.1 Ca (○) and 0.2 Ca (▲).

Fig. 5. The $T$-dependence of $\gamma \equiv C_p/T$ for Bi-2212 with different oxygen contents spanning from underdoped to overdoped (indicated by direction of arrow). The curves for critical and optimal doping are indicated by the bold and dashed curves, respectively. Inset: the doping dependence of the increment in $\gamma$ for Bi$_{2.1}$Sr$_{1.9}$CaCu$_2$O$_{8+\delta}$ (■), Bi$_{1.9}$Pb$_{0.2}$Sr$_{1.9}$CaCu$_2$O$_{8+\delta}$ (×) and Bi$_{2.1}$Sr$_{1.9}$Ca$_{0.7}$Y$_{0.3}$Cu$_2$O$_{8+\delta}$ (▲). In each case, $\Delta\gamma_c$ falls abruptly at $p = 0.19$ with the opening of the pseudogap. $E_g$ values obtained from a scaling analysis are shown by the diamonds.

The doping dependence of $T^*$ - what is the real high-Tc phase diagram?

Knight Shift, Resistivity, Specific Heat

Fig. 4. The doping dependence of $E_g$ for $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{7-\delta}$ from $^{89}K_s$ (○), from heat capacity (+) and from scaling of the resistivity (×), of the condensation energy $U_0$ (●) and of $T_c$ (□).

Superconductivity is Stabilized Near Quantum Critical Points, *but no one knows why.*


Hole-doped High-Temperature Superconducting Cuprate
Maximum $T_c \sim 40\text{-}150$K

Ordinary Metal

Anti-ferromagnet

Superconductor

Pressure (kbar)
0 10 20 30

Temperature (K)
0 5 10

CeIn$_3$
a Heavy Fermion Compound
with Superconducting $T_c < 1$ K
Superconductivity is stabilized near quantum critical points, 
*but no one knows why.*


**Determining the phase diagram of the electron doped superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2**


![Graph showing the phase diagram of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$](image)

**Metallic Magnet**

doping=0.13
As the years go by….
Many Broken Symmetries Discovered at the Pseudogap Onset

K. Fujita et al., Science 344, 612 (2014)
Is the Onset of the Pseudogap a Thermodynamic Transition?
• Sound speeds depend on compressibility, a thermodynamic susceptibility.
• Any phase transition has a signature in the compressibility.
• Let’s see what a superconductor does (theory by an experimentalist).

\[
\begin{align*}
\Delta F|_{T_c} &= H_c^2 \left( T_c, B, P \right) = 0 \\
\frac{\partial \Delta F'}{\partial P}|_{T_c} &= \Delta V|_{T_c} = H_c \frac{\partial H_c}{\partial P}|_{T_c} = 0 \\
\frac{\partial^2 \Delta F'}{\partial P^2}|_{T_c} &= \frac{\partial \Delta V}{\partial P}|_{T_c} = \frac{1}{c_{ij}} = H_c \frac{\partial^2 H_c}{\partial P^2}|_{T_c} + \left( \frac{\partial H_c}{\partial P} \right)^2|_{T_c}
\end{align*}
\]

There is always a step discontinuity at the superconducting transition in elastic stiffness.

Resonant Ultrasound Spectroscopy (RUS) uses the mechanical resonances of small samples to extract all the components of the elastic tensor at the same time.

RUS and other ultrasound techniques measure the adiabatic moduli—typically within 1% of isothermal moduli in solids.

Only RUS measures the true thermodynamic attenuation, independent of defects and scattering, transducer misalignment.

Implementation of a modern resonant ultrasound spectroscopy system for the measurement of the elastic moduli of small solid specimens

Albert Migliori
National High Magnetic Field Laboratory of the Los Alamos National Laboratory, Los Alamos, New Mexico 87545

J. D. Maynard
The Pennsylvania State University, University Park, Pennsylvania 16802

(Received 8 August 2005; accepted 24 October 2005)

The use of mechanical resonances to determine the elastic moduli of materials of interest to condensed-matter physics, engineering, materials science and more is a steadily evolving process. With the advent of massive computing capability in an ordinary personal computer, it is now possible to find all the elastic moduli of low-symmetry solids using sophisticated analysis of a set of the lowest resonances. This process, dubbed “resonant ultrasound spectroscopy” or RUS, provides the highest absolute accuracy of any routine elastic modulus measurement technique, and it does this quickly on small samples. RUS has been reviewed extensively elsewhere, but still lacking is a complete description of how to make such measurements with hardware and software easily available to the general science community. In this article, we describe how to implement realistically a useful RUS system. © 2005 American Institute of Physics.

DOI: 10.1063/1.1940494
Tiny single detwinned crystals are required

YBCO 6.60 Underdoped $T_c=61.6K$
YBCO 6.98 Near optimal $T_c=88.0K$

Made in Canada
By UBC
Bonn, Liang, Hardy
Impossible to do what we did without crystals of this quality

205μm thick
1.03 x 1.2mm
1.62 mg
Resonant Ultrasound Spectroscopy — technique

\[ z = z_\infty + \frac{Ae^{i\phi}}{\omega - \omega_0 + \frac{i\Gamma}{2}} \]
What is normal?
Overall smoothness and normal behavior

Mechanical resonances of a macroscopic crystal

YBCO

Elastic moduli and attenuation in underdoped YBCO at superconducting transition through the looking glass


no attenuation signature

Q=50,000

Functional form around transition not easily understood
Detail of the superconducting transition seen through even stronger looking glass

- Step size depends on superconducting fraction.
- Transition width is sharper than most observations of YBCO.
- Size of jump makes sense if we observed **full thermodynamic signature**: $(T_c/T_f)^2$
  (no preformed pairs).

![Graphs showing superconducting transitions](image)

- **Underdoped**: $1 \times 10^{-4}$ jump
- **Near optimal** (slightly overdoped, $T_c \sim 88$K): $10 \times 10^{-4}$ jump
Pseudogap boundary in YBCO 6.98 (overdoped) \( T_c=88.0 \text{K} \)

Perform a linear component analysis of the temperature dependence of multiple resonances

- Each resonance is a combination of the thermal response of several elastic moduli.
- Deconvolution produces the three types of thermal responses shown at right.

Superconductivity (this feature appears at the same temperature for all resonances)

Dissipation feature at temperatures that track frequency of each resonance (thus not a phase transition)

Pseudogap (this feature appears at the same temperature for all resonances)
Perform a linear component analysis of the temperature dependence of multiple resonances.

Superconductivity (this feature appears at the same temperature for all resonances)

Dissipation feature at temperatures that track frequency of each resonance (thus not a phase transition)

Pseudogap (this feature appears at the same temperature for all resonances)

The precision in determining $T^*$ is determined by the sharpness of the change in slope.
Conclusions from Resonant Ultrasound Spectroscopy

- Pseudogap onset IS a thermodynamic phase transition, conjectured to be second order with a magnetic order parameter.

- Observed evolution of the pseudogap phase boundary from underdoped to overdoped establishes the presence of a quantum critical point inside the superconducting dome.

- This suggests a quantum-critical origin for both the strange metallic behavior and the glue mechanism of superconducting pairing.

Back to High Magnetic Fields...

(up to 60T)

to see Quantum Oscillations
Large Fermi Surface in Tl-2201 in the overdoped regime

Original measurement using Angle-Dependent Magneto-resistance Oscillations:
N.E. Hussey, M. Abdel-Jawad, A. Carrington, A.P. Mackenzie, L. Balicas,

FIG. 1. (Color online) Fast Fourier transform of torque data between 38 and 45 T for Tl26K (red) and Tl10Ka (blue) samples. The data were taken at T=0.35 K. The inset shows the raw data for the two samples.

A.F. Bangura, P.M.C. Rourke, T.M. Benseman, M. Matusiak, J.R. Cooper, N.E. Hussey, and A. Carrington
Fermiology and electronic homogeneity of the superconducting overdoped cuprate $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ revealed by quantum oscillations
2007: Small Fermi Surface in the Underdoped YBCO – The Pseudogap State Looks like an Ordinary Fermi Liquid!


Doping Dependence of Quasiparticle Number

Hall Effect in Single Layer BSLCO

Hall Effect in Single Layer LSCO


Effective Mass and Quasiparticle Number


Yelland et al., PRL 100, 047003 (2008)
Turning it up to “11”...

(Achieved 100T in 2012 for the first time without blowing something up)
What can you do with 1,400,000,000 Watts?

You can power Los Angeles

You can go...

...or you can pulse one magnet
250 Mega Joules = 500 STICKS OF DYNAMITE
March 22, 2012: 100.7T Pulse (Non-destructively!)

Many groups have used the 100T magnet to study quantum oscillations in cuprates. We will focus on recent unpublished work by Ramshaw, et al. that is relevant to the question of a critical point at optimum doping.

YouTube: Search for “100 tesla magnet”
There IS a Quantum Critical Point Near Optimum Doping

K. Fujita et al.,
arXiv (2014)

IN THE UNDERDOPED REGIME:
Magneto-transport finds a low-density metal ... with logarithmic scattering or localization.
ARPES finds arcs.

THE ONSET OF THE PSEUDOGAP:
... is a thermodynamic phase transition, from Resonant Ultrasound Spectroscopy
... is accompanied by many symmetry-breaking phenomena

AT THE TERMINATION OF THE PSEUDOGAP LINE NEAR OPTIMUM DOPING,
The linear-T resistivity persists to lowest temperatures
There are anomalies in the Hall number.
The quasiparticle mass appears to diverge... evidencing enhanced electron interactions

IN THE OVERDOPED REGIME:
Magneto-transport finds a high-density metal.
ARPES finds a complete Fermi surface.
Thank You !
Inducing insulating behavior in optimally doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ by increasing disorder. (Don’t know if this will be log-T)

Resistivity vs T for (a) $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. For increasing Pr the Tc drops and the residual resistivity increases, (b) Ion damaged $YBa_2Cu_3O_{7-\delta}$. After bombardment of 1-MeV Ne$^+$ ions at fluences of (0, 0.1, 2.5, 4.0, 10.0, 15.0, 20.0, and 22.0) $\times 10^{13}$ ions/cm$^2$. For increasing ion damage the behavior is similar for increasing Pr in (a).

Electron tunneling and transport in the high-Tc superconductor $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$

PHYSICAL REVIEW B 50, 3266 (1994)
A. G. Sun, L. M. Paulius, D. A. Gajewski, M. B. Maple, and R. C. Dynes